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Insulated Skin Temperature and Cardiac Frequency as Indices of Thermal Strain during Work in Hot Environments

Nigel A.S. Taylor and Denys Amos

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ABSTRACT

The paper reviews the possibility that thermal strain may be predicted or determined from changes within certain physiological variables. Key variables include body core temperature, cardiac frequency, sweat rate and skin blood flow. The possible use of a modified skin temperature and cardiac frequency are examined as a means of predicting impending heat dysfunction or quantifying thermal strain. The two most promising techniques for possible monitoring of body core temperature are those of insulated transcutaneous and zero-gradient skin temperature measurements.

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Insulated Skin Temperature and Cardiac Frequency as Indices of Thermal Strain during Work in Hot Environments

Executive Summary

During military operations and exercises in northern Australia and during overseas duty, soldiers commonly must operate under a degree of thermal stress from the environment. Such thermal stress has a significant impact upon military operations and performance. As a consequence, quantification of the physiological function within the environment is a critical consideration. The complexity of data acquisition and socially unacceptable nature of some techniques has resulted in a search for easily quantified strain indices which may be used to provide occupational health and safety specialists, and ultimately military commanders, with easily determined, non-invasive surrogate indices for thermal strain.

The physiological variables which can be monitored and which permit prediction of heat strain include body core temperature (T_{core}), heart rate, sweat rate and skin blood flow. The last two variables are hard to measure in the field. The same comment is often raised concerning the measurement of T_{core}, leading to the suggestion that either an insulated or a zero-gradient skin temperature may be used instead of the standard indices of T_{core}.

It is well established that heart rate varies as a function of physical and psychological stress. While heart rate is affected by T_{core}, this interrelationship with other variables means that it cannot be used to predict heat tolerance time successfully. Recent work has explored the possibility of using on-line monitoring of heart rate to regulate thermal and exercise stress. The algorithms used in the evaluation of heart rate are based on sound physiological principles and would adequately meet the requirements of the Australian Defence Force for the monitoring and regulation of heart rate during combined thermal and exercise stress, but would not enable monitoring of thermal strain.

Several conclusions are offered concerning the efficacy of using a single-site skin temperature as a surrogate index of changes in T_{core}. Under hot and humid conditions, changes in skin temperature may appear to provide a more sensitive indicator of heat tolerance time, than do changes in rectal temperature. While the convergence of non-insulated skin and core temperature is a readily observed phenomenon, particularly in clothed persons, it does not provide a means by which impending heat intolerance may be detected. The use of a skin temperature measure as an index of core temperature requires that the former provides a reliable means by which the latter may be tracked. This tracking has yet to demonstrated in clothed personnel. While considerable inter-regional variations in local skin temperature exist, the base of the skull and the forehead appear to be sites showing the closest approximation of core

temperature. Any chosen skin site should either inherently satisfy, or be artificially made to satisfy the following criteria: minimal air movement; dry skin surface; minimal radiant heat exchange with the environment. Of the data reviewed, the two most promising techniques are those of the zero-gradient and insulated transcutaneous skin temperature measures. Since much of the literature is drawn from a diverse range of environmental states, clothing configurations and exercise regimens, there is a need to evaluate the efficacy of this technique under conditions which most closely replicate those to be encountered by the Australian Defence Force.

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Contents

1. Introduction

The ability to tolerate thermal stress, at either end of the thermal spectrum, frequently has a significant impact upon worker performance, and ultimately upon the long- and short-term health of workers, in both industrial and military settings. Consequently, the quantification of both the thermal environment, and physiological function within that environment, is a critical consideration. However, the complexity of data acquisition, and sometimes the socially unacceptable nature of some methods for quantifying thermal stress and strain[1], has resulted in the search for easily quantified stress and strain indices, which may be used to provide the applied scientist and the occupational health and safety specialist with easily determined surrogate indices for these variables. For example, while we know that several attributes of the thermal environment determine its impact upon physiological function (*i.e.* dry bulb and black globe temperatures, wind velocity, air pressure and water vapour pressure), the quantification and interpretation of such variables may be considered both too complex and time consuming within military operations. Numerous, simplified derivations have therefore been developed to approximate such measurements. While both the use of, and the appropriateness of, these methods are the source of some considerable debate within the scientific community (*e.g.* Wenzel *et al.*, 1989), they have been quite widely adopted for use in both industrial and military situations. However, similar simplified methods have not been widely adopted for the quantification of thermal strain. The purpose of this report is to evaluate the possibility that heat tolerance may be predicted, or determined from changes within certain physiological variables.

1.1 Determinants of heat tolerance

An understanding of the factors which predispose to heat intolerance provides the basis for identifying elements which may enable heat tolerance prediction. While a complete review of this topic is beyond the scope of the current report, the following summary provides relevant background information.

Heat acclimation: The single most powerful determinant of heat tolerance is the state of heat acclimation (Kenney, 1985). The methods for, and the physiological adaptations to, heat acclimation have been reviewed recently. (Taylor *et al.*, 1997)

Physical fitness: Habitual physical training has long been known to improve heat tolerance, primarily via its influence upon heat adaptation (Nadel *et al.*, 1974). Furthermore, the rate of rise of the body core temperature (T_{core}) is mainly determined by the relative exercise intensity (Saltin & Hermansen, 1966). Thus, since heat storage

[1] Heat stress refers to the physical properties of the environment (air temperature, relative humidity, radiant heat load), while heat strain quantifies the magnitude of the physiological impact of this stress.

drives T_{core}, then, in general terms, the rate at which the body takes on heat during a given physical task is a function of the relative intensity of the work load.

Obesity: Obesity is associated with a significant reduction in heat tolerance, and differences in thermal adaptation (Buskirk *et al.*, 1965).

Age: Older adults seem to be at greater risk from heat disorders. This is partially due to reduced sweat function (Kenney & Gisolfi, 1986). But this may itself be due to reduced physical fitness that accompanies ageing (Kenney, 1988). Furthermore, older adults are less able to adapt to the heat (Wagner *et al.*, 1972).

From an understanding of these key factors, one has a basis for differentiating between the heat tolerance capabilities of various individuals. However, of these variables, only the first two offer a possible means by which heat tolerance may be either predicted, or identified during the course of an exercise-heat exposure. Since heat acclimation and habitual physical exercise both result in similar adaptations, then differences between adapted and non-adapted individuals may be identified by monitoring changes in certain physiological parameters. But which measurements would allow such an identification? The key variables include: T_{core}, cardiac frequency (*fc*: heart rate), sweat rate and skin blood flow. The last two variables are difficult to measure within the applied setting. The same comment is often raised concerning the measurement of T_{core}, leading to the suggestion that either an insulated (Bernard & Kenney, 1994) or a zero-gradient skin temperature (T_{skin} : Fox & Solman, 1971) may be used instead of the standard indices of T_{core}. Therefore, the purpose of this report is to evaluate the possible use of a modified T_{skin} and *fc* as a means for either predicting impending heat dysfunction, or quantifying ongoing thermal strain.

2. Using skin temperature to approximate heat strain

Heat strain manifests itself through an elevation in body temperatures, both at the body core, and at the body surface (T_{skin}). These elevations are a direct consequence of altered thermal balance. That is, as a result of elevated endogenous (metabolic) and exogenous (externally applied) heat gain, the rate of heat accumulation exceeds the rate of heat dissipation, causing an increase in the rate of body heat storage[2]. Since body tissue temperatures change by a set amount for a given rise or fall in heat storage (specific heat), then the indices of thermal strain (T_{core} and T_{skin}) generally track body

[2] This relationship is defined by the heat balance equation: S = M -(±W) ±E ±R ±C ±K [W·m-2]. Where: S = heat storage (+ for storage; - for loss) [W·m-2]; M = internal heat production (metabolism) [W·m-2]; W = work performed (+: energy leaving system) or received (-: energy entering system) [W·m-2]; E = heat exchange via evaporation (-) or condensation (+) [W·m-2.kPa-1]; R = heat exchange via radiant exchange (loss -; gain +) [W·m-2]; C = heat exchange via convective heat flow (loss -; gain +) [W·m-2]; and K = heat exchange via conductance (loss -; gain +) [W·m-2].

heat storage. While this is a fundamental principle of thermoregulation, it has not universally been applied to attempts to seek an index of thermal strain.

Burton (1935) and Shvartz & Benor (1972) utilised body heat storage to study changes in either body temperature or heat tolerance. Burton (1935) developed a means of using the change in T_{skin} to derive changes in mean body temperature[3]. Shvartz & Benor (1972), used seven subjects across six environmental states, and found that heat tolerance decreased as a power function[4] of the rate of body heat storage ($r = -0.985$). Thus, 97% of the variance in heat tolerance could be explained by changes in heat storage alone. When analysed against changes in mean T_{skin} [5], derived from four sites, heat tolerance was still well correlated ($r = -0.848$). The strength of the former relationship makes one wonder why such a method has not been taken up by other research groups.

Researchers who have attempted to use a skin temperature as a surrogate measure of T_{core}, have compared their chosen gauge with one or more of the widely used indices of T_{core} (*e.g.* oesophageal temperature (T_{es}), tympanic temperature (T_{ty}), auditory canal temperature (T_{ac}) or rectal temperature (T_{re})). While this may be of superior practical relevance, since standard specifications for work restrictions in thermally stressful environments are either based upon thermal stress or T_{core} changes, such an approach assumes that T_{core} indices provide a faithful quantification of changes in heat storage, possessing both similar proportionality characteristics and response time constants. The former attribute may be assumed to exist over the physiologically relevant temperature range, on the basis of our understanding of the specific heat of the body, and how it is affected during heat stress. However, since it is the T_{core} which tracks heat storage, then known lags in the chosen T_{core} index (see: Nielsen & Nielsen, 1962; Snellen, 1969; Saltin *et al.*, 1970) will markedly alter the fidelity of the index. Furthermore, since most surrogate indices of T_{core} are derived directly from changes in T_{skin} [6], it is possible, in typically hot-dry thermal states, with people exercising at light to moderate loads while wearing little or no clothing, that T_{skin} will not track either changes in T_{core} or heat storage. In fact, it has long been known that certain thermal states (*e.g.* fever and some exercise states) drive T_{core} and T_{skin} in opposite directions (Burton, 1935; Nielsen, 1969).

Notwithstanding these reservations, and in due consideration of the practical significance that such a T_{skin} surrogate measure would have to both industrial and military applications, it is worth exploring situations within which these general trends do not occur, and within which such measures may be both possible and valid.

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3 $\Delta T_{body} = (0.65 / 3.8\Delta T_{skin}) + (0.35 * \Delta T_{skin})$.

4 Heat tolerance = $1277.30 \cdot x^{-0.711}$ (min). Where x = rate of heat storage ($cal.m^{-2}.h^{-1}$).

5 Heat tolerance = $3.85 \cdot 10^{19}\ x^{-11.46}$ (min). Where $x = T_{sk}$ (°C)

6 In the semi-nude person, T_{skin} has generally been shown to be dependent upon ambient temperature (T_a) and largely independent of metabolic rate, while T_{core} is primarily dependent upon metabolic rate and independent of T_a across a wide temperature range (Nielsen, 1938).

2.1 The origin of the concept

Given that a stable and uniform body T_{core} does not really exist, but is, instead, more a useful concept than an actual phenomenon (Burton, 1935; Bligh, 1973), then it is doubtful whether determining central body temperature provides an accurate reflection of the temperatures that obtain in other body tissues (Cooper & Kenyon, 1957). Instead, the temperature of any given tissue bed is dependent upon its local heat production, the temperature and flow rate of blood perfusing that bed, and its heat exchange with surroundings tissues (Cranston *et al.*, 1954). Thus, the body has many different temperatures and thermal gradients (Eichna *et al.*, 1951), with the T_{core} recorded at any one site merely being a general indication of the mean central body temperature. However, the concept of utilising a T_{skin} to derive information about the thermal or pathological status of the core is far from novel. For example, T_{skin} has long been used as a diagnostic tool (Gershon-Cohen *et al.*, 1965). Furthermore, if one considers the relative tissue volumes occupied by the core (46%) and skin compartments (54%: Burton, 1938), then it may be possible to conceive of situations in which the T_{skin} may be brought into close proximity to the average T_{core}, especially if the target skin region has been insulated from the influences of environmental temperature.

Iampietro & Goldman (1965) found that T_{core} was not a good indicator of heat tolerance during hot, humid conditions. In such states, they suggested that the T_{skin} after 10 minutes work could be of greater value in predicting work tolerance time. They also suggested that when T_{skin} came to within 1.0°C of T_{core}, work tolerance would be limited. From this work came the concept of T_{core} and T_{skin} convergence, which has been advanced as a method through which impending exercise-heat intolerance may be predicted, and thereby minimised or prevented. Such a convergence means there is no potential for heat dissipation from core to skin, since the thermal gradient between these regions has been removed. Thus, heat is no longer dissipated from the core, and T_{core} will soon commence rapid elevation.

To extend the work of Iampietro & Goldman (1965), Shvartz & Benor (1972) studied subjects wearing vapour barrier suits, to simulate 100% relative humidity, in six thermal states (25°-45°C). They observed that terminal T_{re} and T_{skin} both increased approximately linearly with elevations in ambient temperature (T_a), but the rate of T_{re} rise was slower than that of the T_{skin}. In 45°C, the latter rate was 0.42°C·min^{-1} over the first 10 min, which accounted for 70% of the T_{skin} change. At 30°C, the initial 10-min period accounted for 47% of the T_{skin} change. When T_{skin} converged to within 3°C of T_{re}, there was a rapid storage of heat and an elevation in *fc*. They therefore suggested that heat tolerance may be predicted from changes in T_{skin}.

Perhaps the most frequently cited research on T_{core} and T_{skin} convergence is that of Pandolf & Goldman (1978). They studied heat acclimated subjects wearing clothing of various water vapour permeabilities, in both hot, humid (35°C, 75% relative humidity) and hot, dry conditions (46°C, 10% relative humidity). Subjects performed intermittent

work of various forms (walking, callisthenics, shovelling and bench stepping) for up to two hours. T_{re} and T_{skin} convergence occurred within ~25 min for semipermeable garments, while for more permeable clothing, no convergence was observed. Thus, when clothing permeability, in combination with heat and exercise stresses, creates a hot, humid microclimate, the conditions are created within which T_{skin} will approximate T_{core}, even without the presence of thermal insulation. The authors suggested that such convergence, which indicates the rapid onset of heat intolerance, could be predicted before it occurs, since both the T_{re} and T_{skin} responses follow quite predictable linear trends during such exposures. More recently, Hower & Blehm (1990) have suggested that thermal convergence could form the basis for determining work limits in the heat.

However, it must be emphasised that, so far, researchers have been primarily focussed on subjects wearing various clothing ensembles, and simple extrapolation of these observations to partly clothed or unclothed subjects, even in very humid conditions, may not be justified. Though a close examination of the thermal topography data of Werner & Reents (1980) shows that convergence does occur in the unclothed, resting subject, at an ambient temperature (T_a) between 37°C to 40°C. Furthermore, the interpretation that convergence signals impending exercise-heat failure is not without contention.

Nunneley *et al.* (1992) sought proof that T_{core} and T_{skin} convergence indicated imminent thermal collapse. Their review of the literature revealed that, while convergence was certainly present within the above investigations, and others, it was not a precursor to rapid thermal failure. A closer examination of the data of Shvartz & Benor (1972) revealed that subjects could continue to work for ~30 min after convergence. Similarly, the earlier work of Pandolf *et al.* (1974) showed that convergence had occurred more than 30 min before test termination, and their subjects continued to work in the heat. On this basis, they reinvestigated the association between convergence and thermal collapse. They studied nine exercising subjects across a range of ambient temperatures of 22°C-40°C while wearing either impermeable or semipermeable clothing. Convergence occurred in 42 out of 72 experimental runs (58.3%). In 25 of the 42 convergence cases (59.5%), subjects were able to continue working for 10-45 min beyond the point of convergence. Furthermore, subjects also terminated work before convergence occurred in 18 trials, due to volitional fatigue. When T_{re}, T_{skin} and *fc* were analysed relative to the time of convergence (*i.e.* positive and negative times relative to convergence time), the slopes of each variable failed to reveal changes specifically associated with convergence. That is, neither the time-related response patterns immediately preceding or following convergence differed markedly from one another. Moreover, for trials showing both converging and non-converging trends, the mean T_{re} at test termination was 38.5°C for both response patterns. The authors concluded there was no evidence, either within the literature or in their data, to support the hypothesis that convergence signalled impending heat intolerance, though it does indicate that tolerance time is limited.

2.2 Factors affecting skin temperature

It is apparent that situations do exist where T_{skin} can provide a close indication of T_{core}. It is equally apparent that, within the presently reviewed material, these situations are not present throughout the time course of a given experiment, regardless of the permeability of the clothing used. Consequently, the use of a single T_{skin} may have limited prognostic value under these circumstances. To this point, however, we have been seeking evidence of situations in which T_{skin} equals, or closely approximates T_{core}. However, this may be viewed as a somewhat ideal, if not unrealistic expectation. Instead, it may be equally valuable to find situations within which T_{skin} tracks T_{core}, without the two actually being equivalent. A known and constant offset between the two temperatures would provide the means with which one may be used to approximate the other. To fully explore this possibility, one must understand the factors which affect T_{skin}.

The early work of Burton (1935) indicated that a vertical thermal gradient exists within the skin, more recently confirmed by Nielsen (1969), such that on moving from the central, more stable core, cutaneous temperature decreases parabolically on approaching the skin surface. Thus, T_{skin} is a function of *measurement depth.* This gradient has been shown to be reduced as T_a rises, but is increased as exercise intensity is elevated (Nielsen, 1969). Nielsen (1969) also found that T_{skin} was more closely related to *total heat production* (endogenous and exogenous) than it was to metabolic rate.

LeBlanc (1954) has shown that body composition can affect surface skin temperature. The greater the fat content immediately below the site of measurement, the lower the temperature recorded at that site. Livingstone *et al.* (1987), using thermography on resting subjects, showed the influence of *subcutaneous adipose* to be ~1.6°C when comparing lean and more obese subjects.

Saltin *et al.* (1970) observed that T_{skin} was influenced by *exercise intensity.* At low and medium intensities, T_{skin} was dependent primarily upon T_a ($r = 0.96$)[7], for T_a ranging between 10°-30°C. At heavy exercise levels, T_{skin} appeared driven by both factors, thus concurring with the observations of Nielsen (1969) noted above. The T_{skin} elevation was delayed (~6 min at 30°C; ~10 min at 20°C), and continued to rise for ~5 min after exercise ceased. The critical observation was that at 30°C, the change in T_{skin} paralleled that observed for T_{es}.

Hunold *et al.* (1992) investigated skin temperature patterns of the thigh and arm in resting and exercising subjects using thermography. T_{skin} patterns showed remarkable consistency within subjects, but differed between subjects. Within subjects, the distribution after exercise was more distinct, with greater resolution appearing between the warmer and cooler regions. However, the mean thermal gradient was 0.8-1.0°C·cm^{-1}. Thus, for sites 4-6 cm apart, the temperature difference was up to 3°C.

7 $T_{sk} = 0.391 \cdot T_a + 22.2$

Clearly, there is a prominent *positional influence* determining the absolute temperature measured. T_{skin} fell at start of exercise, tracking cutaneous vasoconstriction, and was then elevated as exercise progressed. The same pattern was seen for the arms, which were inactive. Observations on skin blood flow (laser-Doppler flowmetry) revealed that the increase in T_{skin} was due to increased cutaneous blood flow. That is, *skin blood flow* is a major determinant of T_{skin} (see also: Ohara, 1960), with the influence of local muscle temperature being minimal. Local thermal hot spots appeared to be related to sites where blood reached the surface, before spreading out over skin surface. Thus, such hot spots, and the intra-regional thermal variation, are determined by the *anatomical arrangement* of the cutaneous blood vessels.

In summary, the four major factors which appear to dominate the regulation of T_{skin} are exercise intensity, total heat production, cutaneous adiposity and skin blood flow. Accordingly, and in consideration of ergonomic factors, suitable sites for taking T_{skin} measurements for use as indices of T_{core} would possess the following general attributes: (a) convenience of access; (b) suitable for prolonged measurements; (c) local temperatures at the site should generally be uninfluenced by either environmental changes or atypical cutaneous blood flow patterns; (d) the site should have a minimal layer of subcutaneous adipose insulating it from the body core; and (e) the T_{skin} changes should be quantitatively similar to those observed within the body core.

2.3 Possible skin temperature recording sites

Benedict & Slack (1910) reported a parallelism between the temperatures of the axilla, groin and the cupped palms. More recently, Barnes (1967) postulated that, due to the reciprocal emission and absorption of radiant heat, natural body cavities, if deep enough, should show T_{skin} higher than those observed on exposed flat surfaces[8]. These sites should also be relatively insensitive to ambient changes, and T_{skin} should approach T_{core}. Moreover, such sites should experience minimal air movement, they should have a dry surface so that evaporative cooling has a minimal influence upon their T_{skin}, and heat exchange due to external sources of radiation should be minimal. Using these criteria, the following natural body cavities were identified: the open mouth, nostrils, navel, inner canthus (inner corner of the eye at junction of eyelids), auditory canal (T_{ac}). Using infra-red thermography and oral temperature (sublingual) as the T_{core} index, the T_{skin} of these regions (and other local sites) were studied in 10 subjects. Only T_{ac} tracked oral temperature. In descending order the other temperatures were: inner canthus = 35.4°C; mouth = 34.8°C; navel = 34.6°C; forehead = 34.2°C; and the nostrils provided the lowest local temperature (31.6°C), being lower even than the T_{skin} of the palm, and reflecting the influence of air flow on evaporative cooling at that site. The fact that this was less apparent in the open mouth was possibly a reflection of the nasal breathing pattern employed at rest. Any change to oral

8 The time constant for T_{skin} changes is approximately 3 min (ISO, 1992).

breathing, which typically occurs during exercise, will result in a similar cooling effect upon open mouth temperature.

Olesen & Fanger (1973) found that the T_{skin} distribution, in clothed (0.6 clo) resting subjects, was less uniform for women (SD = 1.43°C) than it was for men (SD = 1.04°C); possibly a simple reflection of differences in subcutaneous adiposity. In male subjects, the sites of highest skin temp were (in descending order): the lower occiput (base of the rear of the head at the neck): 34.7°C, right abdomen: 34.7°C; right scapula: 34.5°C; forehead: 34.3°C; left upper chest: 34.2°C; right anterior thigh: 33.8°C; right upper arm: 33.7°C; left hand: 33.7°C; right foot instep: 33.3°C; left posterior thigh: 32.9°C; left lower part of upper arm (above elbow): 32.8°C; right shin: 32.7°C; left shin and calf: 32.4°C. Of these sites, one would tend to choose the lower occiput, since it is both easily accessible and has the highest resting temperature. However, this region does contain a considerable amount of subcutaneous adipose, which varies between individuals.

Werner & Reents (1980) investigated T_{skin} topography across T_a ranging from 10°-50°C. In supine subjects (wearing only shorts), T_{skin} varied widely (17°C) in the cold, but became more uniform in the warmer exposures. The following T_{skin} rankings were observed (hottest-coldest): (a) at a T_a of 10°C, T_{skin} ranged from ~12-~29°C: forehead, abdomen, chest, thigh, back, upper arm, forearm, calf, hand, foot, finger, toe; (b) at 20°C, T_{skin} ranged from ~20-~32.5°C: forehead, abdomen, chest, thigh, back, upper arm, forearm, calf, hand, foot, finger, toe; (c) at 30°C, T_{skin} ranged from ~30.5-~35.5°C: forehead, abdomen, thigh, hand, chest, forearm, back, upper arm, finger, calf, foot, toe; and (d) beyond 35°C, T_{skin} ranged from ~34-~36°C, but the plots do not permit differentiation between sites. In these conditions, the forehead provides consistently higher T_{skin} values. It also contains minimal and consistent subcutaneous adipose deposits across subjects. However, its sweat rate is among the highest observed, and this will influence T_{skin} (Ohara, 1960). Given that the microclimate under clothing during an exercise-heat exposure will be ~35°C, if not greater, then many skin sites appear suited. However, we know little about the variability of these sites during exercise, when subjects are wearing clothing. We do know, however, that clothing reduces the difference between the core and skin surface temperatures (Hower & Blehm, 1990).

The chest thermograms of Livingstone *et al.* (1987) have revealed large variations in T_{skin} (up to 3.5°C), as reported above by Hunold *et al.* (1992). Thus, single T_{skin} readings were inaccurate reflections of the mean T_{skin} for the chest. The T_{skin} recorded from a single skin thermistor was found to vary by as much as 3°C from the corresponding mean T_{skin} determined by thermography. This accuracy improved when the skin was warmer. The thermograms at 28.0°C indicate that the skin regions above the xiphoid process (fanning out along the clavicles) gave the highest and most uniform T_{skin}.

In summary, while we know that T_{skin} reveals considerable intra-region variability, and that natural body cavities (except for the auditory canal) are of little value for

approximating T_{core}, we do know that inter-regional differences in T_{skin} make some sites better suited to this purpose. Furthermore, we know that clothing tends to minimise the T_{core}-T_{skin} gradient. Thus, if we apply the general principles suggested above by Barnes (1967) to the skin surface (*i.e.* minimal air movement, dry skin surface, and minimal radiant heat exchange), then we may be able to find a surrogate index of T_{core}.

2.4 Modified local skin temperature

While the concept of using a skin temperature to approximate deep body temperature has been attempted previously for both clinical and research purposes, only two groups have attempted to modify the microclimate at a single site, as a means of replicating either the T_{core} or tracking its dynamic response during endogenous and exogenous thermal strain. Both techniques may be collectively described as transcutaneous thermometry.

The first technique employs a zero-gradient approach, where the temperature of a combined heating and insulation pad, positioned over a designated skin region (sternum), was brought up to that of the skin surface immediately below the pad (Fox & Solman, 1971, Fox *et al.*, 1973; Solman & Dalton, 1973: for details See: *Appendix 1*). In this manner, it was suggested that the temperature of the body core was exteriorised (Fox & Solman, 1971), in the same manner that locally applied heat will arterialise capillary blood. This zero-gradient principle has similarly been applied to the measurement of T_{core} via the auditory canal temperature (Keatinge & Sloan, 1975; Moore & Newbower, 1978), where the thermal gradient within the auditory canal is removed, hence allowing auditory canal temperature to be measured without the influence of environmental effects upon skin temperature.

Fox *et al.* (1973) have shown that this instrument can faithfully track changes in auditory canal (insulated), rectal and abdominal temperature (radio-pill) induced by either thermal stress or artificially-induced fever. The transcutaneous temperature was usually slightly lower. However, it was relatively unaffected by T_{skin}, which varied between 26^{o} and 35^{o}C. This independence was maintained even when T_{skin} was falling. During exercise, it was found that when the level of exercise was high, or when exercise was conducted in the cool, there was a divergence between the transcutaneous temperature and the T_{core}. These discrepancies could perhaps be overcome by using a larger probe size. However, during mild exercise in a warmer climate, the correlation was again sound. This group did not test subjects at air temperatures above 29^{o}C, so it is recommended that further research be undertaken to evaluate this device at higher T_a.

More recently, Smith *et al.* (1980) completed a 10-day field trial in which this zero-gradient transcutaneous temperature was compared with oral temperatures recorded at various intervals throughout the day. The rank correlation between these two

measures was 0.78, but a number of spurious readings were observed when the microclimate exceeded the specifications of the device (25°-40°C).

Bernard & Kenney (1994) have taken another approach to the same problem. They have described a method which utilises the methods employed in heat flux transducers. An insulated disk (0.8 cm thick and 4.2 cm diameter) was placed over a sandwich of three copper disks (each 2.5 cm diameter), with thermocouples attached to the rear of each disk. This device was then positioned on the chest. Trials on 51 subjects wearing impermeable (exercising at 55°C) and permeable clothing (exercising at 45°C) were conducted. Output from the thermocouples was compared with the T_{re} response. The authors reported a high correlation between the temperature of the disk closest to the skin and T_{re} (r = 0.93). Accordingly, they have recommended that a single-site insulated T_{skin} be used as a possible substitute for the more traditional indices of T_{core}. They do not claim that such a temperature is the T_{core}, merely that "it may be used to predict excessive" T_{re} rises (p. 507).

3. Using cardiac frequency to gauge heat strain

It has long been known that cardiac frequency (*fc*) is correlated with body core temperature (T_{core}). For example, Tanner (1951) found that 31% (r = 0.565) of the variance in the supine resting *fc* was due to variations in rectal temperature[9] (T_{re}) alone. Thus, an elevation in T_{re} of 1.0°C will elevate resting *fc* by approximately 15 $b{\cdot}min^{-1}$. The ISO (1992) suggests that, while there is considerable individual variation, even within the same subject, one can expect *fc* to rise by as much as 33 $b{\cdot}min^{-1}{\cdot}{}^{o}C^{-1}$ rise in T_{re}. This elevation will be independent of the nature of the heat source (endogenous versus exogenous), being instead dependent upon the total body heat content. Given that it is universally recommended that the T_{core} not be allowed to rise more than 1.0°C above its resting level within the working environment, then an elevation of ~30 $b{\cdot}min^{-1}$ above that typically observed for a given task, has been recommended as a criterion for changing work patterns or implementing work-rest cycling (ISO, 1992).

It is also well established that *fc* varies as a function metabolic rate, static exertion, psychological stress, and is influenced by both circadian and breathing rhythms (ISO, 1992). Thus, while a 30 $b{\cdot}min^{-1}$ *fc* threshold may be appropriate for sedentary (resting) workers, it may not be considered appropriate to the more active worker. To address this issue, Shvartz *et al.* (1977) attempted to predict thermal tolerance from changes in both *fc* and T_{re} determined during a 15 minutes bench stepping task, completed at 23°C. Thermal tolerance was evaluated during a 3 hour stepping test conducted at 39.3°C. For both variables, subjects were given arbitrary ratings between 10 (low *fc* or

9 *fc* = $8.15{\cdot}T_{re}$ (oF) - 742.98 b·min-1.

T_{re}) and 100 (high *fc* or T_{re}). These divisions were made up by dividing the *fc* range from <105 to >168 $b{\cdot}min^{-1}$ into 10 equally spaced groups. Similarly, T_{re} values were divided equally across the range from 37.5 to 38.4°C, in divisions with 0.1°C increments. The composite score for each subject was derived from a simple average of these two scores, computed at 23° and 39.3°C. The composite scores from the two trials were then correlated[10] ($r = 0.94$). This strong correlation shows that heat tolerance can be successfully predicted from a 15 minutes test undertaken at 23°C. This prediction was possible only because the changes in *fc* and T_{re} were correlated between the two trials (*i.e:* a high *fc* or T_{re} at 23°C is associated with high values at 39.3°C). However, *fc* alone could not be used to successfully predict tolerance time.

More recent work by Bernard & Kenney (1994) has involved a study of the possibility of using on-line monitoring of *fc* as a means of regulating thermal and exercise stress. These authors have developed a personal monitoring system which records an insulated skin temperature (see: Section 2.4), and *fc*. The algorithms used in the evaluation of *fc* have been eloquently presented, and are based upon sound, and well established physiological principles. In short, the monitor uses safety thresholds to warn the worker when *fc* exceeds prescribed limits. These limits are established from a consideration of the worker's age, the anticipated work tolerance time at any given work rate, and the occurrence of transient *fc* peaks during the working day.

In summary, the algorithms which have been used by Bernard & Kenney (1994) to regulate *fc* are both appropriate and sufficiently sensitive for general application within industrial and military settings. Accordingly, *it is our view that this system would adequately meet the requirements of the Australian Defence Force, for the monitoring and regulation of heart rate during combined thermal and exercise stress.* However, this recommendation does not extend to the temperature monitor aspect of this sytem.

4. Conclusions

On the basis of the above review, the following conclusions are offered concerning the efficacy of using a single-site skin temperature (insulated or otherwise) as a surrogate index of changes in body core temperature, for use by ADF personnel during exercise in hot, humid environments.

(1) In general, heat tolerance appears to be more precisely predicted from changes in body heat storage than from changes in one or more skin temperatures.

(2) Under hot and humid conditions, changes in skin temperature may provide a more sensitive indicator of heat tolerance time, than do changes in rectal temperature.

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10 $y = 1.07x - 3.33$. Where: y = composite score in the heat (39.3°C); x = composite score at 23°C.

(3) While the convergence of skin and core temperature is a readily observed phenomenon, particularly in clothed persons, it does not provide a means by which impending heat intolerance may be detected.

(4) The use of a skin temperature measure as an index of core temperature requires that the former provides a reliable means by which the latter may be tracked. With the exception of the insulated and zero-gradient skin temperature methods, this tracking has yet to identified.

(5) Local skin temperatures are influenced by: subcutaneous adipose; exercise intensity; total heat production; and local skin blood flow.

(6) While considerable inter-regional variations in local skin temperature exist, the lower occiput (base of the skull) and the forehead appear to be sites showing the closest approximation of core temperature.

(7) Any chosen skin site should either inherently satisfy, or be artificially made to satisfy the following criteria: minimal air movement; dry skin surface; minimal radiant heat exchange with the environment.

(8) Of the literature reviewed, the two most promising techniques are those of the zero-gradient and insulated transcutaneous skin temperature measures.

(9) In conclusion, there exists a need to assess one or more of these techniques within situations of direct relevance to the military or industrial group to whom they may be applied. That is, since much of the literature is drawn from a diverse range of environmental states, clothing configurations and exercise regimens, there is a pressing need to evaluate the efficacy of this technique under conditions which most closely replicate those to be encountered by the Australian Defence Force.

(10) The algorithms used by Bernard and Kenney (1994) to monitor and regulate *fc* are appropriate for general application within the ADF for monitoring and regulation of heart rate during combined exercise and thermal stress.

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The accompanying references are not only related to the contents of this report, but provide additional useful reading pertinent to this topic.

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Appendix 1

The Cambridge Deep Body Temperature Equipment

The first commercially available device used to determine changes in body core temperature from a measure of skin temperature was developed by the National Institute for Medical Research (U.K.). This transcutaneous method was developed as a non-invasive, comfortable technique which could be used for extended durations (Fox & Solman, 1971, Fox *et al.*, 1973; Solman & Dalton, 1973).

The device (Cambridge Deep Body Temperature Equipment) is a multi-layer sandwich (6 cm * 6 cm * 0.6 cm) containing two independent thermistors, housed within a single silicone rubber pad. One thermistor lies in contact with the skin surface, being separated from the second thermistor by a layer of nylon gauze and silicone rubber. Both thermistors form arms of a Wheatstone bridge. The extent to which the bridge is out of balance gives an indication of the difference in thermistor temperature. Above the second thermistor is a thin-film heater element, driven by a servo-heater, which heats the outer surface of the pad to the same temperature as the skin thermistor, thereby balancing the Wheatstone bridge signal. In this manner, a region of zero heat flow is created over the underlying skin region. It is, therefore, believed that the temperature of the body core is exteriorised (Fox & Solman, 1971), in much the same manner that a locally applied heat source will act to arterialise capillary blood. The device operates over the range from 29-42^{o}C, but with suitable electronic support could be adapted to cover a wider thermal range.

Fox *et al.* (1973) have shown that this instrument can faithfully track changes in auditory canal (insulated), rectal and abdominal temperature (radio-pill) induced by differences in thermal stress. The transcutaneous temperature was usually slightly lower. However, it was relatively unaffected by skin temperature, which varied between 26^{o} and 35^{o}C. This independence was maintained even when skin temperatures were falling. During exercise, it was found that when the level of exercise was high, or when exercise was conducted in the cool, there was divergence between the transcutaneous temperature and the body core temperature. These discrepancies could perhaps be overcome by using a larger probe size. However, during mild exercise in a warmer climate, the correlation was again sound. This group did not test subjects at air temperatures above 29^{o}C.

A very similar device has been developed for measuring auditory canal temperature (Keatinge & Sloan, 1975). This instrument, currently held within the Thermal Physiology Research Laboratory (University of Wollongong), works on a similar servo-heater principle, and is designed to remove the thermal gradient within the auditory canal, hence allowing auditory canal temperature to be measured without the influence of thermal affects upon skin temperature.

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19. ABSTRACT

The paper reviews the possibility that thermal strain may be predicted or determined from changes within certain physiological variables. Key variables include body core temperature, cardiac frequency, sweat rate and skin blood flow. The possible use of a modified skin temperature and cardiac frequency are examined as a means of predicting impending heat dysfunction or quantifying thermal strain. The two most promising techniques for possible monitoring of body core temperature are those of insulated transcutaneous and zero-gradient skin temperature measurements.

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